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THE ORIGIN OF THE ZINC DEPOSITS AT FRANKLIN AND STERLING HILL, NEW JERSEY

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The origin of the zinc deposits at Franklin and Sterling Hill, New Jersey, is a question of great interest to the student of mineralogy and ore deposits. Several excellent summaries of the geology, with its numerous problems of structure, petrology, and metamorphism, and of the mineralogy and paragenesis of the ores have appeared in recent years.¹

Each of these authors has presented his interpretation of the origin as a result of his studies of the area. There is general agreement as to the fundamental elements in the geology of the area and the occurrence and mineralogy of the ores, but the authors of each of the last four papers published on the subject have presented evidence favoring as many different methods of origin. The very uniqueness of the mineralogy of the zinc ores: franklinite, willemite, and zincite, (unlike any other zinc deposit in the world) makes their origin an entrancing problem. The origin of the great group of rare minerals developed by the intrusion of the pegmatites into the ores or their vicinity has been correctly interpreted, the writer believes, by Spencer, Ries and W. C. Bowen, and Palache. The magnetite deposits cannot be ascribed to the same source or time as the zinc deposits. They are probably of a later date.

The recent excellent paper by Professor Palache, giving a paragenetic classification of the minerals of this region is ac-

¹ Spencer, A. C., *U. S. Geol. Survey, Franklin Furnace Folio*, No. 161.

Ries, H. and Bowen, W. C., *Origin of the Zinc Ores of Sussex County, N. J., Econ. Geol.*, vol. 17, pp. 517-571, 1922.

Spurr, J. E. and Volney, J. Lewis, *Ore Deposition at Franklin Furnace, New Jersey, Eng. and Min. Jour.-Press*, vol. 119, pp. 317-328, 1925.

Palache, Charles, *Paragenetic Classification of the Minerals of Franklin, New Jersey, Am. Mineralogist*, vol. 14, pp. 1-18, 1929.

accompanied by an expression of his theory as to the origin of the deposits. The writer, who is in essential agreement with Professor Palache's theory, had considerable hesitancy in writing this. He had, however, developed the same theory independently some years ago and has been teaching it to his classes in ore deposits. Somewhat the same theory was independently developed also by R. H. Rastall² of Cambridge University and is given in his volume on "The Geology of the Metalliferous Deposits." The writer discussed the origin of these minerals with Dr. Rastall in 1925, and in August of that year visited and studied the mines for a few days. The objective in writing this paper is to present a discussion of the simple chemical and mineralogical method by which the present mineralogy of the deposit was brought about, probably something like what Palache had in mind but which he did not develop.

The writer will not review in detail the geology of the area in this paper as it has been adequately presented in Palache's paper, so recently, as well as in other papers cited. This paper will present the writer's theory as to the composition of the original ore body, its change into an oxidized body, and its final conversion into the present ore body, and the evidence for the theory.

CHARACTER OF THE ORIGINAL DEPOSIT

The present zinc ore is a folded tabular body in the Franklin limestone (marble) of pre-Cambrian age. The limestone is generally believed to be a part of, or equivalent in time to, the Grenville series.

No other known zinc ore body consists of a group of minerals like those in this deposit, *i.e.*, franklinite, willemite (and tephroite), and zincite. These minerals do not occur in any type of deposit directly connected with igneous rocks, or in those not connected with them. The New Jersey deposit has been metamorphosed, regionally, subsequent to the deposition of the ores. We are thus led to conclude that the deposit which became the source of this unique ore body was similar to the hundreds or even thousands of zinc deposits scattered over the earth's surface, and which constitute our chief source of zinc.

In these common deposits, the chief zinc mineral is sphalerite, oxidized, in greater or less degree, to smithsonite or hemimorphite

²Rastall, R. H., *The Geology of the Metalliferous Deposits*, pp. 131, 305, 1923

or, rarely, willemite. It is associated with varying amounts of other sulfides including pyrite or marcasite, galena, and chalcopyrite. Like the sphalerite, these sulfides undergo alteration in the zone of oxidation. A great many gangue minerals occur with these zinc ores. These include carbonates, sulfates, oxides, and silicates. Some deposits are notably simple in their mineralogy and others are very complex.

Using the metals found in the New Jersey deposit (the ratio of Zn:Fe:Mn is 3:3:1) as a basis for deducing the mineralogy of the original ore body, it is believed that that deposit consisted (in the order of their probable abundance) of sphalerite, pyrite or marcasite, calcite, and rhodochrosite. This represents a maximum of simplicity in mineralogy, but it must not be thought that other minerals might not have been present. Quartz or an unknown silicate may have been present, and a manganiferous siderite may have been present. If galena were present in the original deposit, the modern ore body was separated from it during oxidation. Galena, however, is not believed to have been present. It is possible that the ore solutions may have introduced some manganese into the calcite in the limestone surrounding the ore body, but this occurred more probably during the period of oxidation.

This aggregate of minerals, sulfides and carbonates, was deposited in the Franklin limestone (probably while it was a limestone) by solutions from an unknown source. It is not improbable that some part of the Pochuck gneiss may have been the source rock, but such a suggestion is only conjectural. The simple mineralogy suggests a deposit near the surface.

OXIDATION OF THE ORIGINAL SULFIDE DEPOSIT

The next step in the development of the zinc deposits was the oxidation of the postulated primary ore body. This would occur if the ore body was brought to or near the surface. The oxidized products, again, were relatively few. The sphalerite was converted into the carbonate (smithsonite) and the hydrous silicate (hemimorphite). The iron sulfide (or sulfides) was oxidized and became hematite or limonite. The rhodochrosite was probably oxidized, in part at least, to manganite, pyrolusite, and braunite.

The hydrous zinc silicate, hemimorphite, was more abundant in the oxidized deposits than was smithsonite. The deposits at

Moresnet, Belgium,³ and at Granby, Missouri,⁴ are similar types, as both occur in limestone. Hemimorphite occurs in more complex ores also, as at Leadville, Colorado,⁵ and in a small mine in southwestern New Mexico described by Blake.⁶

The source of the silica that entered the hemimorphite is of interest. Had the original ore body been near an igneous rock, as at Leadville and in the New Mexico deposits, a source would have been at hand. Likewise, the deposit at Granby, Missouri, had an adequate source in the chert of the associated limestone. Rastall⁷ suggests that the original rock at Franklin might have been a siliceous limestone, but this does not appear to have been possible, for the present limestone or marble is very pure, containing, for the most part, less than one per cent of silica, and rarely reaching 2.5 per cent. Quartz does not appear as a gangue mineral of the present ores. That it may have been present in the original ore body is entirely possible, but if so, it has been converted into hemimorphite (and braunite). The most probable source for the silica appears to have been the weathered mantle rock, or an overlying, or nearby, shale or sandstone. Minor amounts may have been derived from the limestone itself, and, also, from quartz or silicates in the original ore. It is unlikely that there was so complete a balance between any original quartz and the zinc as to leave *no* quartz in the ores. Furthermore, there was a deficiency of silica, as is shown by the presence of smithsonite. It is probable that the silicate formed after the carbonate (possibly in part replacing it), although if silica were in the oxidizing solutions, the silicate might be formed first or at the same time. The hemimorphite in the Moresnet deposits is in limestone. Some of the silicate ore bodies in those deposits are very large, hence the amount of original silica must have been considerable. Its source is unknown; very probably it came from the limestone or from some nearby slates. The hemimorphite of the

³ Beyschlag, Vogt, and Krusch, *Ore Deposits*, vol. 2, p. 731, see also p. 735.

⁴ Buckley, E. R. and Buehler, H. A., *The Geology of the Granby Area, Mo. Bur. of Geol. and Mines*, vol. 4, 1905.

⁵ Emmons, S. F., *Geology and Mining Industry of Leadville, Colo., U. S. Geol. Survey*, Mon. 12, 1886.

Emmons, S. F., Irving, J. D. and Laughlin, G. F., *Geol. and Ore Deposits of the Leadville Mining District, Colo., U. S. Geol. Survey, Prof. Paper 148*, 1927.

⁶ Blake, W. P., *Zinc Ore Deposits near Hanover, New Mexico*, *Trans. Am. Inst. Min. Eng.*, vol. 24, pp. 187-195, 1894.

⁷ Rastall, R. H., *ibid.* p. 305.

New Jersey deposits contains about six or seven per cent of manganese oxide (MnO), but is essentially free from ferrous oxide, a fact characteristic of the smithsonite also, as noted below.

Zinc carbonate is more insoluble than calcium carbonate, and is, therefore, a common alteration product of sphalerite, especially in limestone. Both manganese and iron are isomorphous with zinc in the carbonate and may replace it in any amount. The following analyses are quoted from Doelter⁸ to show the wide range in composition of smithsonite in one area. The table gives the composition of the oxidized zinc deposits in Aachen, Prussia, (near to and similar to those at Moresnet, Belgium).

PERCENTAGES	
ZnCO_3	84.92 to 40.43
FeCO_3	1.58 to 53.24
MnCO_3	6.80 to 2.18
CaCO_3	1.58 to 5.09
MgCO	2.84 — —
	<hr/>
	97.92 100.94

The smithsonite in the deposits at Franklin and Sterling Hill is very low in ferrous iron, as will be pointed out later, but contains about six per cent of manganese oxide.

The iron sulfide of our original ore body was oxidized to hematite and limonite, as has been said. The sulfate radical, thus freed, may have been a factor in introducing the manganese into the calcite, for manganese is readily transported as the sulfate. A significant feature of the oxidation and hydration of the iron sulfide was the completeness of the process. As there is practically no ferrous oxide in any of the present ore minerals, all the iron must have been oxidized. Pyrolusite and manganite were formed but apparently not in abundance. Braunite appears to have been formed also. The amounts of the different manganese oxides are difficult to estimate.

There is no evidence that there were any deposits of the so-called "tallow" or zinciferous clays in connection with the oxidized deposits. Aluminous minerals do not occur in the ores; undoubtedly, if there had been any originally, they would still be present, as such minerals are very difficult to remove.

The mineralogy of the oxidized ore body (exclusive of the cal-

⁸ Doelter, C., *Handbuch der Mineralchemie*, vol. 1, p. 444.

cite), in the order of abundance, is believed to have been as follows:

1. Iron and manganese oxides, anhydrous and hydrous.
2. Hydrous zinc silicate (hemimorphite).
3. Zinc carbonate (smithsonite).
4. Manganese carbonate (rhodochrosite).

Other minerals may have been present but it is not necessary to assume this, because the mineralogy as outlined above is adequate to fully account for the origin of the actual minerals in the present ore body.

FORM AND POSITION OF THE OXIDIZED ORES

The tabular form of the present ore bodies is, no doubt, similar to the shape of the original bodies. The curved or hooked shape is due to subsequent folding. Aside from the thickening the deposits have undergone as a result of folding and flowage, they are essentially as originally deposited. Thus the originals were, we assume, tabular bodies.

Two probabilities exist as to their original position. One is that they were residual masses on the surface, but resting upon and replacing the underlying limestone. The other is that they were tabular or bedded deposits wholly within the limestone.

Examining the possibilities of the first premise, we find that the deposit must have been wholly on the surface and unassociated with clays, for there are no aluminum silicates in the ore proper (there were some associated with the metamorphism due to the pegmatites, but they were derived from the pegmatites). Residual iron and manganese ores resting on the surface, as we find them today, illustrate the probable original form and position of the zinc ore body, but such present deposits, rarely, if ever, are entirely free from clay materials.

This objection in the matter of clay would apply to the possible derivation of the zinc ores from a deposit such as the secondary accumulation of hemimorphite, "smithsonite, zinciferous clay and iron and manganese hydrates" at Sterling Hill, described by Palache. There can be no question that this combination of minerals would be a possible source for a fränklinite-willemite-zincite-ore, *if it were not for the clay*. Had clay been originally present, some evidence of it would undoubtedly still be found in the ores, for it is almost impossible to remove aluminum silicates from a deposit. The zinc minerals would have been removed long before the aluminum silicates were.

It seems necessary, therefore, to assume that the oxidized material was a tabular mass within the limestone, because if the original, primary sulfide mass was altered in place or transported and replaced a bed within the limestone, the change would have taken place by solutions free from any aluminous substances. If the oxidized ore body was due to oxidation in place, the form and position of the original body must have been tabular. If it was due to replacement by solutions, the structural or lithological features of the rock controlled the form and position. The ore body may have developed along a fissure of some type, or along some readily replaceable bed, either of which possibilities would (or could) permit the development of the tabular character of the deposit. The branching of the bed at Sterling Hill could be readily explained as replacement along a branching fissure.

Another point favorable to the idea that the oxidized ore body was wholly within the limestone is the fact that the present ore bodies at both Mine Hill (Franklin) and Sterling Hill are entirely surrounded by the Franklin limestone. A surface deposit would, of necessity, have to be infolded to be so surrounded.

ORIGIN OF THE PRESENT ORE MINERALS

The conversion of the carbonates and hydrous minerals of the oxidized ore body into the anhydrous silicates and oxides of the present zinc deposit represents the next step in origin of the deposits. The ancient pre-Cambrian limestone has been deeply buried and intensely metamorphosed by heat and pressure since the oxidized ores near the old land surface were developed. All the minerals in the original rock have been recrystallized. Locally, they are coarsely crystalline aggregates.

The extent of the metamorphism is only conjectural. The pressure was great enough to cause the limestone, or more correctly, the marble, to flow, distorting included rock masses and warping and folding the tabular ore body, and, as at Mine Hill, even completely shearing off a portion of the ore body itself. This movement was to the north and east according to Spurr and Lewis.

The source of the heat necessary to produce the metamorphism may be two-fold: (1) that resulting from deep burial, and (2) that due to intrusion beneath, or nearby, of a batholithic mass, as postulated by Spurr and Lewis. The alteration of the oxidized

zinc ores preceded the injection of the pegmatites (also a pre-Cambrian event), which may have had their source in such a batholith but were injected long after the metamorphism of the ores.

THE MINERAL ALTERATIONS INVOLVED

The oxidized ore body containing the zinc, iron, and manganese is believed to have had the following mineral composition (in the order of abundance):

1. Hydrous iron-manganese oxides.
 - (a) hematite— Fe_2O_3 .
 - (b) limonite— $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$.
 - (c) braunite— $3\text{Mn}_2\text{O}_3 \cdot \text{MnSiO}_3$.
 - (d) manganite— $\text{Mn}_2\text{O}_3 \cdot \text{H}_2\text{O}$.
 - (e) pyrolusite— MnO_2 .
2. Hydrous zinc silicate.
 - (a) hemimorphite— $\text{Zn}_2\text{SiO}_4 \cdot \text{H}_2\text{O}$
(usually very pure)
3. Zinc carbonate.
 - (a) smithsonite— ZnCO_3
(Manganese and iron may replace the zinc, but there is very little iron in this material.)
4. Manganese carbonate.
 - (a) rhodochrosite— MnCO_3
(This mineral like the ZnCO_3 may contain isomorphous mixtures of Zn and Fe. Very little if any ferrous iron present.)

This order is based upon the relative abundance of the minerals in the present ore as given by Palache and furnished to him by the New Jersey Zinc Company. Palache's table follows.

MINERALOGICAL COMPOSITION OF THE FRANKLIN ORE

Ores	Percentages
Franklinite	43
Willemite	26
Zincite	1
Other silicates, (garnet, rhodonite, tephroite (?) etc.)	5
Calcite	25

This ore body is believed to have been wholly within the limestone. The chemical changes necessary for the production of the present minerals are few and simple. They comprise dehydration and decarbonation changes (there is but scanty evidence of deoxidation) accompanied by a recrystallization of the ore body and country rock alike. Aside from the simple heat reactions of

dehydration and decarbonation, the entire series of chemical reactions takes place among the three isomorphous elements: iron, manganese, and zinc.

The microscopic studies of Ries and Bowen showed that there was a definite sequence in the recrystallization (regarded as crystallization by them, as they hold the ores are metasomatic replacements) of the ore minerals. That sequence is as follows:

1. $\left\{ \begin{array}{l} \text{willemite—} 2\text{ZnO} \cdot \text{SiO}_2 \\ \text{tephroite—} 2(\text{Mn}, \text{Zn}, \text{Mg}, \text{Fe}) \text{O} \cdot \text{SiO}_2 \end{array} \right.$
2. franklinite— $(\text{Mn}, \text{Zn}, (\text{Fe}?)) \text{O} \cdot (\text{Fe}, \text{Mn})_2 \text{O}_3$
3. zincite— ZnO

As the table quoted from Palache's paper shows, franklinite is the most abundant mineral in the ores, willemite next, and zincite last. Palache does not include tephroite in the list, but states that it is "an occasional rare accompaniment of willemite." It has been included in this analysis of the origin of the deposits because it is, even though rare, a constituent of the primary ores.

Analyses of all the primary ore minerals are given in the tables that follow. When critically studied, these analyses reveal some rather astonishing facts concerning the presence of certain oxides, and the distribution of the essential elements: iron, zinc, and manganese, among them. The analyses are taken from Dana's "A System of Mineralogy," sixth edition.

COMPOSITION OF FRANKLINITE (Dana. p. 227)

Locality	Percentage Composition of Each Constituent						
	Fe_2O_3	Mn_2O_3	ZnO	MnO	FeO	Total	Others
Mine Hill (Franklin), N. J.	63.40	4.44	23.12	10.46	—	101.42	
Mine Hill (Franklin), N. J.	60.52	6.79	19.44	12.81	—	99.56	
Mine Hill (Franklin), N. J.	56.57	10.52	15.91	16.37	—	99.37	
Sterling Hill, N. J.	67.42	—	6.78	9.53	15.65	100.04	$\text{Al}_2\text{O}_3 = .65$
Sterling Hill, N. J.	67.38	—	16.28	16.38	—	100.04	
Sterling Hill, N. J.	66.34	—	20.26	12.31	—	98.91	
Average	63.60	7.25*	16.96	13.98			

* Average of 3 only.

COMPOSITION OF WILLEMITE (Dana, p. 461)

Locality	Percentage Composition of each Constituent					
	SiO ₂	ZnO	MnO	FeO	Total	Others
Theoretical Composition	27.00	73.00	—	—	100.00	
Sterling Hill, N. J.	27.40	66.83	5.73	0.06	100.20	MgO = trace, H ₂ O = 0.18
Sterling Hill, N. J.	27.92	57.83	12.59	0.62	100.38	MgO = 1.14, H ₂ O = 0.28
Mine Hill (Franklin), N. J.	27.20	65.82	6.97	0.23	100.22	
Mine Hill (Franklin), N. J.	26.92	65.04	7.78	0.51	100.25	
Mine Hill (Franklin), N. J.	28.30	66.68	4.92	0.31	100.21	
Mine Hill (Franklin), N. J.	27.48	63.88	8.33	0.49	100.18	
Mine Hill (Franklin), N. J.	27.14	64.38	6.30	1.24	99.06	
Mine Hill (Franklin), N. J.	27.75	60.61	10.04	1.80	100.20	CaO = trace
Average			7.83	0.66		

COMPOSITION OF ZINCITE (Dana, p. 208)

Locality	Percentage Composition of each Constituent				
	ZnO	MnO	Fe ₂ O ₃	Total	
Sterling Hill, N. J.	93.28	6.50	0.44	100.22	
Sterling Hill, N. J.	94.30	5.54	0.36	100.20	
Average	93.79	6.02			

COMPOSITION OF TEPHROITE (Dana, p. 458)

Locality	Percentage Composition of each Constituent								
	SiO ₂	MnO	FeO	ZnO	MgO	CaO	ign.	Total	
Theoretical Composition	29.80	70.20	—	—	—	—	—	100.00	MgO usually present
Sterling Hill, N. J.	30.19	65.59	1.09	0.27	1.38	1.04	0.37	99.93	
Sterling Hill, N. J.	30.55	52.32	1.52	5.93	7.73	1.60	0.28	99.93	
Sterling Hill, N. J.	31.73	47.62	0.23	4.77	14.03	0.54	0.35	99.27	
Mine Hill, (Franklin) N. J.	29.44	57.31	0.87	7.36	2.50	2.51	0.27	100.26	
Mine Hill, (Franklin), N. J.	30.63	49.80	3.33	5.74	10.16	—	—	99.66	
Mine Hill, (Franklin) N. J.	29.95	36.43	1.96	11.61	18.60	—	1.71	100.26	
Average		51.51	1.33	5.94	9.06	0.95			

The composition of franklinite, as shown by these analyses, reveals the very significant fact that all the iron present is *ferric iron*, with the exception of one specimen. The analyses of five specimens do not show any ferrous iron. The formula for franklinite, if based upon these analyses, would be written somewhat differently. Yet the fact that ferrous oxide is isomorphous with the ZnO and MnO would make its presence theoretically possible in the mineral. The willemite also is essentially free from ferrous oxides, the average of eight analyses of the mineral from the Franklin area being only 0.66 per cent. The tephroite shows an average of 1.33 per cent ferrous iron in six specimens, but the very small percentage of this mineral present in the ores reduces this amount of ferrous iron to insignificant proportions. Zincite contains no ferrous iron, but has a little ferric oxide, doubtless included as an impurity. The absence of ferrous iron in all but one analysis of franklinite and the very small quantities of it in the other ore minerals is strong proof for the writer's theory of a fully oxidized ore body as the source of the present ores.

Another feature of significance is the presence of MnO in all the minerals. The average content for each, and the number of analyses is given in the following table.

AVERAGE PERCENTAGE OF MnO IN THE ORE MINERALS

	Number of Analyses	Per Cent MnO
Willemite	8	7.83
Franklinite	6	13.98
Zincite	2	6.02
Tephroite	6	51.51

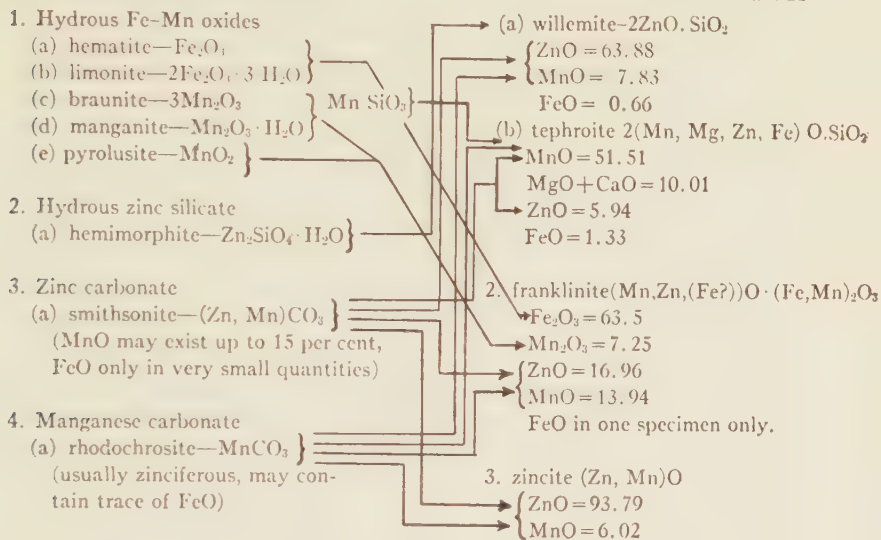
Willemite and zincite are dominantly zinc minerals, but the franklinite contains an average of only 16.96 per cent and the tephroite 5.94 per cent ZnO. Thus we see that the minerals are dominantly zinc-manganese minerals. The only one containing significant amounts of iron is franklinite, and its iron is in the ferric state. The six analyses given of franklinite show an average of 63.6 per cent ferric oxide. Three of these analyses show Mn_2O_3 isomorphous with the ferric iron. Franklinite is the only mineral in the deposit that contains manganic oxide.

Still another point of interest is that the tephroite of the district contains an average percentage of 9.06 MgO, larger than either the FeO or ZnO content. It has also an average content of 0.95 per cent of CaO making about 10 per cent of these two oxides. The formula for tephroite should be $2(\text{Mn}, \text{Mg}, \text{Zn}, \text{Fe}) \text{O} \cdot \text{SiO}_2$, if based on the material in the Franklin area.

In order to show graphically the sequence of chemical changes taking place, the following chart has been made. The minerals in the oxidized ore body are on the left and arranged in the order of their probable abundance as already indicated. The resulting ore minerals are found on the right, but arranged in the order of their recrystallization as determined by Ries and Bowen.

ORIGINAL OXIDIZED ORE MINERALS

PRESENT ORE MINERALS



The dehydration of iron and manganese oxides and the zinc silicate would begin as soon as the temperature was raised, either by dynamic action or by igneous intrusion. According to Doelter,⁹ limonite may begin to lose its water at 50°C and is dehydrated at 150°C. Hemimorphite does not lose its water until heated red hot. Decarbonization of zinc silicate begins at a very low temperature, 90°C. according to Doelter. Manganese carbonate does not lose its CO_2 until at a high temperature. Unfortunately, no determinations as to the temperature at which some of these minerals finally lose their H_2O or CO_2 are available. Some evidence bearing on the temperatures is shown in the burning of clays. The hydrous iron oxides lose their water early in the firing. Calcite (the chief gangue mineral of the ore) loses part of its CO_2 at about 812° to 825° C. Such temperatures as these exceed the temperature of many magmas, and it seems improbable that the temperature of the Franklin limestone and its ores ever exceeded those given above. Furthermore, the reactions of the oxides with each other would certainly take place at lower temperatures and thus permit the carbon dioxide and water to go free.

⁹ Doelter, C., *ibid.*, vol. 3, pt. 2, p. 714.

The dehydration of the hemimorphite accompanied by decarbonization of, or reaction with, the MnCO_3 would give rise to the willemite (the FeO in this mineral being derived from the MnCO_3 as hemimorphite never shows any FeO). The tephroite was formed from the MnSiO_3 , of braunite, uniting with Zn_2SiO_4 and MnCO_3 , or possibly with ZnCO_3 , in a dolomite. The franklinite was formed by the dehydration of the limonite, manganite, and the slightly hydrous hematite and pyrolusite, in the presence of ZnCO_3 and MnCO_3 . The one specimen (there may be others in the deposits) containing FeO was evidently formed from the reaction of an iron-rich zinc or manganese carbonate with the other oxides. Any excess of ZnCO_3 became ZnO and was either manganeseiferous, originally, or reacted with some MnCO_3 to become so.

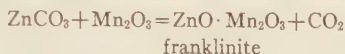
There is no reason to assume that these reactions took place rapidly, although they undoubtedly were all completed within one period that antedated the intrusion of the pegmatites. The pre-Cambrian period was long, and thus there was ample time for an infinite number of reactions to have taken place.

The oxidized minerals involved are all commonly found in oxidized deposits, and many are found in the same association. They do not represent impossible combinations. It may be asked why braunite was assumed to have been present rather than rhodonite, and the answer is that rhodonite is more typically a mineral of certain vein deposits and is frequently found in schists. It could not be stated that it was not present, however, and if it was, it might well have been converted into tephroite.

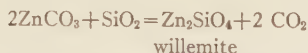
The reactions are dominantly temperature effects and attendant recrystallization. Deoxidation is not demanded. Two simple oxides: manganous and zinc, appear in every mineral, along with manganic and ferric oxides. If manganese dioxide (pyrolusite) was present in the oxidized ores, it would lose a part of its oxygen as the heat in the rocks increased and become Mn_2O_3 . This is a simple laboratory method of preparing Mn_2O_3 . The silicates which were formed merely acquired isomorphous elements made readily available by the decarbonation of the carbonates already intergrown with them and favored by the temperature. A more striking illustration of the part isomorphism may play in the formation of a series of minerals would be difficult to find.

A comparison of the above changes with those suggested by Rastall will disclose several wide differences. Some of his sug-

gestions are evidently impossible, as for instance, his reaction:



and



Silica may have been present, but the evidence is against it. The franklinite of the district contains 63.60 per cent ferric oxide, indicating the presence in the original deposit of hydrous iron oxides.

The theory of Ries and Bowen that the deposits are due to the replacement of limestone (the writer believes that the oxidized ores accomplished this) leaves one entirely in the dark as to the source of the solutions. These authors do not draw for us any concept as to the character of the solutions, doubtless because they recognized the difficulties involved. So far, no one has given us a concept as to the type of solution that could transport and deposit this unusual aggregate of minerals. The process outlined by the present writer does not call for any reactions out of the ordinary.

THE LIMITS OF THE PRESENT DISCUSSION

The writer has made no attempt to discuss the general geology or the details of the occurrence of the ore bodies. Neither has he discussed the pegmatites, or the development of the long list of rare minerals. He believes they have been fully and accurately described by the authors listed at the beginning of this paper. He does not subscribe to all the details as given by them, but does feel that the sequence of events is much as has been described by Spencer, Ries and Bowen, and Palache, and, to a certain extent, by Spurr and Lewis.

The theory advanced here seeks only to trace the events that gave rise to the present zinc-manganese ore body before it was altered locally by subsequent intrusions. The writer believes that the mineralogy advanced here, and the reactions given, account, in a simple and reasonable manner, for the unique mineral aggregate of the present ore deposit.

CAPSULAR SILICA

FREDERICK A. BURT, *A. & M. College of Texas.*

OCCURRENCE

Three specimens of capsular silica have been collected by the writer from the Quaternary formations of Brazos County, Texas. Clastic fragments of petrified wood are very common in these formations, and much opal and botryoidal chalcedony is found as veins and incrustations with the wood. The Tertiary and Quaternary formations of the county are exceptionally rich in precipitated silica which occurs as quartz, chalcedony, and opal. These three minerals are found in the forms of petrified wood, veins, rock cement, silica-limonite hardpan, case-hardening, septaria, and melikaria.¹



FIG. 1

A portion of the surface of the largest specimen. The photographed area is about 2 centimeters across and shows the whole, or the major part, of 4 cubes and parts of several others. Some of the cubes are complete, but the majority are only partly developed and interlock with the next adjoining cube.

¹ Burt, Frederick A., Melikaria: Vein Complexes Resembling Septaria Veins in Form, *Jour. Geol.*, vol. 36, p. 539 (1928).

The capsular silica occurs as a layer occupying the position of a replacement of the bark of the wood. The layer averages 4 to 5 millimeters in thickness, with a maximum thickness of 15 millimeters. The appearance of the mineral is that of a group of fully, and partially developed isometric crystals of cubic habit, superimposed upon the free faces of which are regular capsules arranged in two systems at right angles to each other. The cubes are variously oriented, and interlock with one another (Figure 1). The individual cubes vary from 4 to 9 millimeters across, with an average nearer the larger number.

In close association with the capsular silica are found pieces of petrified wood incrustated with very much smaller cubes of quartz. The exposures of the formations containing these various forms of silica show efflorescences of halite and many cubic crystals of pyrite. These cubes of quartz are interpreted as pseudomorphs after one or the other of these minerals.

PHYSICAL AND CHEMICAL CHARACTERS

The mineral is translucent, and nearly colorless to pale blue in small pieces or thin sections. When viewed in mass a light agate blue is pronounced. The luster is similar to that of opal. No cleavage was observed and the fracture is typically conchoidal. Hardness of the capsules is 6.5. Specific gravity 2.63. They are slowly soluble in potassium hydroxide.

The following analysis shows the composition of the mineral.

Analysis of Capsular Silica²

SiO ₂	98.70 %
Fe ₂ O ₃	1.25
Al ₂ O ₃	0.37
H ₂ O	0.00
Total	100.32

OPTICAL CHARACTERS

Thin sections of the mineral, under crossed nicols, are seen to consist of a compact mosaic of silica units (Figure 2). Higher magnification shows these units to be composed of quartz intermingled with finely fibrous chalcedony. Inclusions of limonite are fairly common, especially along cracks and in contact with

² Analysis prepared for this paper by J. P. A. Zeller, Chemist of the Texas Engineering Experiment Station.

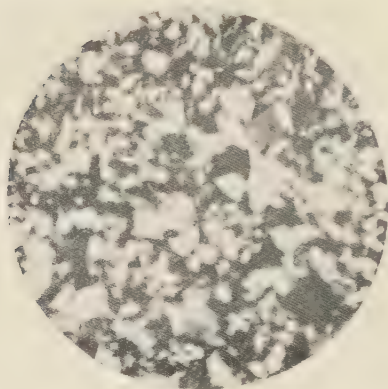


FIG. 2

Typical section, under crossed nicols, from the interior of cube. (96X). Sharply outlined quartz crystals, fibrous, and incompletely extinguished areas are visible. The dark areas are of sharply extinguished quartz.

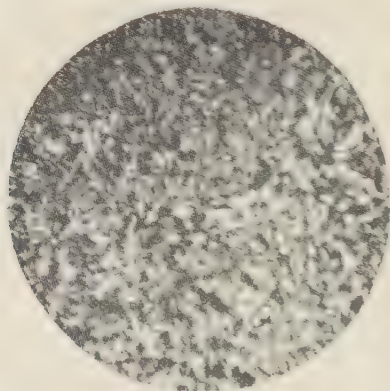


FIG. 3

Low power (20X) view under crossed nicols showing division of the cubes into coarse- and fine-grained sections.

the underlying silicified wood. Spherulitic structures are disseminated throughout the mass.

The extinction of both the quartz and the chalcedony is sharp. Extinction in the chalcedony is parallel to the fibres. Elongation of the fibres is negative.

The cubes are not zoned, but are divided into distinct areas. In some cases these areas are distinguished by differences in the coarseness of crystallization (Figure 3). In other cases they are separated by bands of very coarsely fibrous chalcedony. The coarse- and fine-grained areas cannot be correlated with definite depths within the cubes.

The capsules superimposed upon the cubes are composed of very coarsely fibrous chalcedony which extends inward into the cubes like inverted cones (Figure 4). The fibres of these cones are elongated in planes making angles of from 20° to 25° with the surfaces of the cubes.

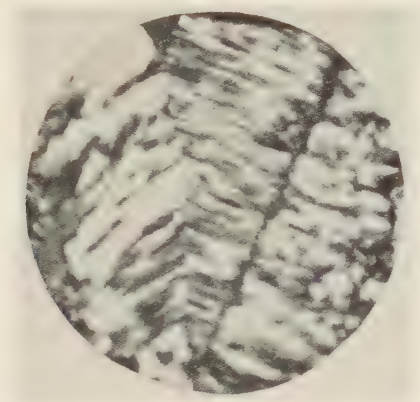


FIG. 4

Vertical section of a cube under crossed nicols (80X). Cone of coarsely fibrous chalcedony extending downward below one of the capsules into the quartz matrix of the cube below.

THEORY OF ORIGIN

The explanation of the origin of the capsular silica involves three problems: (1) the source of the silica, (2) the origin of the cubic form, and (3) the origin of the symmetric system of regular chalcedony capsules superimposed on the free surfaces of the quartz and chalcedony cubes.

The writer advances the following theory to account for these pseudo-crystals.

1. The ground water of the area is known to be carrying silica, much of it presumably in colloidal form as sodium silicate.³ This

³ Brayton, H. R.; Personal communication quoted by Frederick A. Burt, *op. cit.*, p. 542.

silica served as the source of silica for the formation of the capsular cubes.

2. The silica was deposited as a replacement, probably of pyrite crystals, thus giving the individual pseudomorphs their cubic forms.

3. The replacement was an intermittent, rather than a continuous process, resulting in an external quasi-zoning. The free edge of each layer, being unrestricted in its growth, developed a rounded surface according to the well known tendency of colloform minerals.

4. The deposition of the silica of the capsules may have been in the form of hydrogel opal, which by subsequent dehydration and devitrification was converted into chalcedony, or it may have been directly as microcrystalline chalcedony. As some microcrystalline minerals occur in colloform,⁴ and as strain phenomena which might have been produced by dessication is not conspicuous within the capsules nor in their close proximity, the probabilities are that the silica was originally precipitated as chalcedony.

⁴ Rogers, Austin F.; A Review of the Amorphous Minerals, *Jour. Geol.*, vol. 25, p. 518 (1917).

STRUCTURAL REASONS FOR ORIENTED INTERGROWTHS IN SOME MINERALS

JOHN W. GRUNER, *University of Minnesota.*

INTRODUCTION

Many examples of oriented intergrowths are known.¹ In some mineral occurrences it seems to be almost the rule. The well known ilmenite lamellae along the octahedral planes of magnetite have been a subject for discussion for many years. On the other hand, the oriented intergrowth of silver and dyscrasite, which seems to be quite common, has been described only recently.² In other cases where oriented intergrowths might have been expected as in pyrrhotite and pentlandite none seem to exist. The case of tetrahedrite and chalcopyrite appears to be unusual. Oriented layers and crystal growth of chalcopyrite on tetrahedrite crystals have been mentioned frequently, but the microscopic oriented intergrowth of chalcopyrite and tetrahedrite has not been observed.

This paper deals with examples of oriented intergrowths so familiar to workers using the metallographic microscope. The writer is indebted to Prof. G. M. Schwartz of the University of Minnesota for assistance in the microscopic investigation of some of the intergrowths here described.

EXAMPLES OF INTERGROWTHS

There have been a number of suggestions in the literature³ as to the reasons for oriented intergrowths. Some investigators lay considerable stress upon the similarity of the chemical composition of the intergrown minerals. This is justified, probably, in cases of such intimate intergrowths as will be here discussed,

¹ Müggie, O., Die regelmässigen Verwachsungen von Mineralien verschiedener Art, *Neues Jahrb., Beil. Bd.* 16, 1903, p. 335.

² For literature see: Schwartz, G. M., Dyscrasite and the Silver Antimony Constitution Diagram, *Am. Mineral.*, vol. 13, 1928, pp. 495-504.

³ The references are numerous and widely scattered. Often the subject is merely touched upon in a few sentences. The first investigators who used X-ray data in the interpretation of oriented intergrowth seem to have been R. Gross and N. Gross (see under "Sphalerite and Chalcopyrite"). After this paper had gone to press the writer found M. L. Royer's "Recherches expérimentales sur l'épitaxie en orientation mutuelle de cristaux d'espèces différentes," *Bull. Soc. Min.*, Vol. 51, No. 1-2, 1928. Royer describes chiefly experiments with artificial salts.

but it would not apply to the oriented growth of hematite in mica, for example. It seems to the writer, however, that in the common, natural, intergrowths at least one of the important elements of the two formulas should occur in both minerals. The reason most frequently advanced for oriented intergrowth is that the two planes which are in contact have very similar arrangements and spacings of atomic positions. The author would even go a step farther and suggests that in most cases these atomic or ionic positions are occupied by atoms or ions of the same element. The contact plane, therefore, would fit into the structure of one crystal as well as into that of the other. The linear differences in the spacing of the atoms in the two planes in which the crystals meet do not seem to be greater in any case than ten percent of the larger of the two structures that were examined.

MAGNETITE-ILMENITE AND MAGNETITE- HEMATITE INTERGROWTHS

Many writers have called attention to the microscopic ilmenite or hematite lamellae which occupy positions parallel to the octahedral planes of magnetite. Mügge⁴ was one of the first to study these intergrowths. He suggested that the lamellae of ilmenite or hematite are basal plates (0001). This has been verified by the writer by employing reflected polarized light. This orientation of (0001) of ilmenite or hematite parallel to (111) of magnetite may be demonstrated on a polished section containing grains of magnetite cut parallel to (111). The ilmenite or hematite in such a section forms a more or less complete network or equilateral triangles. Extinction of the lamellae occurs whenever they are parallel to one of the vibration directions of the nicols. Ramdohr⁵ describes a section of ilmenite in which magnetite lamellae parallel to (111) are in contact with (0001) planes of ilmenite. The writer⁶ suggested three years ago that the orientation of ilmenite with respect to magnetite must be due to similarity of the contact plane. A study of the structures of the two minerals bears out this belief. Every third and seventh (111) structure plane of

⁴ Über die Mikrostruktur des Magnetit und verwandter Glieder der Spinellgruppe und ihre Beziehungen zum Eisenoxyd, *Neues Jahrb., Beil. Bd. 32.*, 1911, p. 511.

⁵ Beobachtungen an Magnetit, Ilmenite, Eisenglanz, etc., *Neues Jahrb., Beil. Bd., 54, A*, 1926, p. 346.

⁶ Magnetite-Martite-Hematite, *Econ. Geol.*, vol. 21, 1926, p. 388.

magnetite consists of oxygen ions only. These have the arrangement shown in Fig. 1. The ilmenite structure according to Goldschmidt⁷ and Zachariasen is very closely related to that of hematite. The distribution of the oxygen atoms seems to be practically

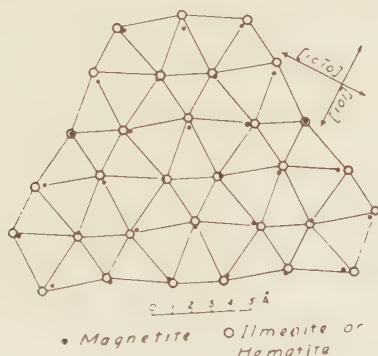


FIG. 1

The (0001) plane of O atoms of ilmenite or hematite superimposed on an O plane (111) of magnetite

identical in the two structures. Every third plane parallel to the base (0001) consists of O ions.⁸ This arrangement is superimposed on the magnetite plane in Fig. 1. The crystallographic directions $[110]$ of magnetite and $[10\bar{1}0]$ of hematite (or ilmenite) have been observed to be normal to each other in the intergrowths described by Mügge.⁹ These two directions are indicated in the structures planes of Fig. 1. They are also normal to each other in the crystal structures. Therefore crystallographic and structural relationships point to the conclusion that this oriented intergrowth is made possible by the sharing of one oxygen plane by both crystals. The spacing of the ions in this common plane is probably neither exactly that of hematite or ilmenite, nor that of magnetite, but about half way between the two values given. Any stresses set up at the contact plane could be gradually distributed over the ionic layers close to the plane.

⁷ Goldschmidt, V. M., *Geochemische Verteilungsgesetze der Elemente VIII, Skrifter Utgitt av Det Norske Videnskaps-Akad., Oslo, I Matem.—Naturvid. Kl.*, 1926. p. 150.

⁸ Structure of hematite: Ewald, P. P. and Hermann, C., *Strukturbericht*, 1913–1926, p. 242; *Zeit. f. Krist.*, attached to vols. 65, 66, 67, 68, & 69.

⁹ *Neues Jahrb., Beil. Bd.*, 16, 1903, p. 347.

HEMATITE-ILMENTITE INTERGROWTH

The structures of these two minerals are so similar in arrangement and spacing of the oxygen atoms that the frequent oriented intergrowth is not surprising. The two minerals usually intergrow parallel to (0001), but intergrowth parallel to (10 $\bar{1}$ 1) has also been noticed.¹⁰ There is no reason why there could not be other orientations where structural resemblance is so complete.

MAGNETITE-SPINEL INTERGROWTH

These two minerals are isomorphous. Their structures are the same, except for a slightly larger unit cell in magnetite. The well known oriented intergrowths of spinel lamellae parallel to the cubic (100) planes of magnetite are easily explained. Every second plane parallel to (100) is an O plane in both minerals. The O plane should become the plane of contact in preference to the others. The latter consist of ferrous or ferric Fe and Mg or Al ions, respectively. An exchange of Fe and Mg or Fe and Al would probably be necessary in the contact plane under those conditions.

SPHALERITE-CHALCOPYRITE INTERGROWTH

R. Gross and N. Gross¹¹ determined the structure of chalcopyrite and noticed its resemblance to sphalerite.¹² The tetragonal character of chalcopyrite is due to the fact that in the sphalerite structure (taken as a structure type) every odd Zn (001) plane has been replaced by Cu, and every even one by Fe. The S positions have been shifted slightly in the direction of the *c*-axis. Gross explains the oriented growth of chalcopyrite on faces of sphalerite parallel to (100) by the similarity of the size and arrangement of the unit cell. He did not mention possible intergrowths along a mutual sulphur plane (100), as the writer has illustrated in Fig. 2. Since chalcopyrite is tetragonal the spacing of the S atoms in the plane parallel to the base (001) is slightly different from that parallel to the second order prism (100) which is shown in Fig. 2. The (001) plane of chalcopyrite, however,

¹⁰ Ramdohr, P., *op. cit.*, p. 356.

¹¹ Die Atomanordnung des Kupferkieses und die Struktur der Berührungsfächen gesetzmässig verwachsener Kristalle, *Neues Jahrb., Beil. Bd.*, 48, 1923, pp. 128-134.

¹² For illustrations of the two structures see this Journal, vol. 14, 1929, pp. 184, 185.

agrees also with the cubic plane of sphalerite. Its S positions are indicated by crosses in Fig. 2.



FIG. 2

The (100) plane of S atoms of sphalerite in contact with the (100) and (001) planes of chalcopyrite.

No mention was made by Gross of the intergrowth parallel to the (111) plane which is probably as common, if not more so, as that parallel to (100). Along (111) the close agreement of the two S planes is shown in Fig. 3. It is not quite correct however, to speak of the S atoms of chalcopyrite in Fig. 3 as being in one plane. On account of the tetragonal symmetry of the crystals the S atoms are not at the corners of equilateral triangles. Alternate rows of S atoms from top to bottom in Fig. 3 lie in the same plane. The two resulting parallel planes (111) of chalcopyrite, however, are so very close together that for the purpose of this discussion they may be considered as one.

It is significant that no microscopic intergrowth has been observed along the dodecahedral planes (the II order pyramid and I order prism of chalcopyrite) along which the spacing agrees as well as in the other planes. These planes contain half sulphur, half metal atoms. It is thought that the fact that the Zn atoms in sphalerite coincide with the Cu and Fe atoms of chalcopyrite in these planes prevents intergrowth or at least causes preferred

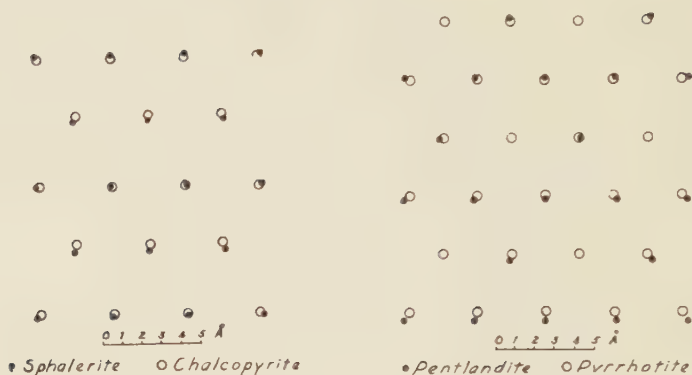


FIG. 3

Positions of S atoms in the (111) planes of sphalerite and chalcopyrite.

FIG. 4

Positions of S atoms in the (0001) plane of pyrrhotite
and in the first (111) S plane of pentlandite.

intergrowth along directions where complete chemical agreement exists.

CHALCOPYRITE-BORNITE AND BORNITE- CHALCOCITE INTERGROWTHS

Much has been published on the microscopic intergrowths of these minerals.¹³ Their mutual planes of contact are the (111) planes for chalcopyrite and bornite, as well as for bornite and chalcocite. In his first manuscript the author had predicted that when the structure of bornite became known it would be found that its contact plane would be very similar in atomic spacing and arrangement to that of chalcopyrite and chalcocite, respectively. A few days after submitting the manuscript to the editor the writer received the description of the structure of bornite from Delft, Holland.¹⁴ A study reveals that the arrangements of the S atoms in chalcopyrite and bornite are very similar. The spacing of the S atoms in the (111) planes of bornite is almost identical to that of sphalerite (3.84Å to 3.83Å). Fig. 3, therefore, can be used for showing the agreement of the (111) S planes in the

¹³ See for example: Schwartz, G. M., Experiments bearing on bornite-chalcocite intergrowths, *Econ. Geol.*, vol. 23, 1928, pp. 381-397.

¹⁴ W. De Jong, Over de Kristalstructuren van Arsenopyriet, Borniet en Tetraëdriet, (Thesis) *Delft*, 1928.

intergrowth of chalcopyrite and bornite as well as of chalcopyrite-sphalerite. The (111) Cu planes in bornite also agree closely with the (111) Cu-Fe planes of chalcopyrite. A decision, therefore, whether the common contact plane is a sulphur or metal plane cannot be made at present.

A comparison of the structures of bornite and cubic chalcocite¹⁵ shows the same similarity for the (111) S planes and (111) Cu planes, respectively. The S as well as Cu atoms are arranged in equilateral triangular fashion in the (111) planes. In bornite the distances between S atoms (or Cu atoms) in these planes would be 3.84 Å and in chalcocite it would be 3.95 Å, a difference of approximately three percent for the two minerals. Again, it is impossible at present to decide whether the contact is along a common S or Cu (111) plane.

The fact that no microscopic intergrowth takes place along other than the (111) planes is also explainable by a study of the structures, for neither cubic nor dodecahedral planes of bornite are similar in atomic arrangement to chalcopyrite or chalcocite.

CHALCOPYRITE-PYRRHOTITE INTERGROWTH

Oriented intergrowth of these two minerals does not seem to be very common, but it has been described by G. M. Schwartz.¹⁶ It can be explained in the same way as the previous examples. The (0001) structure planes in pyrrhotite are S planes alternating with metal planes. The arrangement and spacing in the S planes is shown in Fig. 5. If this plane is superimposed on the S plane of chalcopyrite, in Fig. 3, the linear spacing agrees within 8 percent (3.73 Å:3.43 Å).

CHALCOPYRITE-STANNITE INTERGROWTH

The oriented microscopic intergrowth of chalcopyrite in stannite has been described by G. M. Schwartz¹⁷ and S. Reinheimer.¹⁸ R. Gross and N. Gross¹⁹ also mention it and show the structural

¹⁵ Ewald, P. P., and Hermann, C., *op. cit.*, p. 150.

¹⁶ A Sulphide Diabase from Cook County, Minnesota, *Econ. Geol.*, vol. 20, 1925, p. 264.

¹⁷ Stannite, its Associated Minerals and Their Paragenesis, *Am. Mineral.*, vol. 8, 1923, p. 164.

¹⁸ Chalkographische Untersuchungen an Zinnkies, *Neues Jahrb., Beil. Bd.*, 49, 1923, pp. 163-165.

¹⁹ *Op. cit.*, p. 133. They give the wrong axial ratio for stannite.

hexagonal unit cell contains only two atoms in equivalent positions while a molecule of dyscrasite apparently contains four atoms three of which are equivalent. Machatschki, therefore, believes that Ag_3Sb is a solid solution similar to the hexagonal close-packed solutions of Ag-Zn, Ag-Sn, Ag-Cd, and Ag-In. It is difficult to understand, however, why such a solid solution should always have the same composition and a structure distinct from silver. Silver has no cleavage while dyscrasite has excellent basal cleavage similar to antimony. One is reminded by this property of so-called "layer lattices"²³ Since the Sb atoms seem to have no definite positions assigned to them in the lattice, one is tempted to imagine that Sb atoms segregate in certain layers parallel to the base. Dyscrasite then would be composed of (0001) silver layers (containing some Sb atoms) alternating with a few layers containing an excess of Sb over silver. As Sb resembles Ag in mass as well as in radius it is doubtful, whether X-ray powder diagrams could record such discrepancies. Besides, Machatschki²⁴ mentions several unexplained anomalies in his investigation.

Regardless of how the Sb atoms are distributed the fact remains that the arrangement and spacing of the atomic positions in the (0001) plane of dyscrasite and in the (111) plane of silver are practically (within three percent) alike. Their contact plane would be a possible plane in both structures, especially since the cubic silver lattice can dissolve up to 14 percent of antimony.²⁵

ABSENCE OF ORIENTED INTERGROWTHS IN PYRRHOTITE PENTLANDITE MIXTURES

So far we have been able to explain the occurrences of oriented intergrowths on the basis of internal structures of the minerals. The question now arises: Why are there no true oriented intergrowths in the mixtures of pyrrhotite and pentlandite, especially since pentlandite is supposed to be one of the components of the "unmixing" of a solid solution of $(\text{Fe}, \text{Ni})\text{S}$? R. W. Van Der Veen²⁶ gives one illustration of pentlandite in pyrrhotite that seems to show some slight orientation, but the writer would

²³ Gruner, J. W., Crystal Structure Types, *Am. Mineral.*, vol. 14, 1929, pp. 173-187.

²⁴ *Op. cit.*, p. 174.

²⁵ Machatschki, F., *op. cit.*, p. 175.

Schwartz, G. M., *op. cit.*, p. 495.

²⁶ *Mineragraphy and Ore Deposition*, The Hague, 1925, Fig. 16.

hesitate to state definitely that it represents an oriented intergrowth. W. H. Newhouse²⁷ seems to have seen a similar intergrowth of pentlandite "sometimes extending into the pyrrhotite crystal from an intergranular mass of pentlandite." This may signify replacement along the parting planes of pyrrhotite, but not true oriented intergrowth.

Considerable differences exist in the two structures.²⁸ Pyrrhotite is hexagonal and more closely packed than pentlandite. The bonds or valence coördinates for each metal and S atom are six in number to six atoms of opposite charge. Odd numbered (0001) planes are metal; even numbered are S planes. The spacing of the atoms in these planes are shown in Figs. 4 and 5. The arrangement of S in cubic pentlandite in (111) planes is superimposed on pyrrhotite. It will be noticed that the S atoms shown almost coincide, but that there are "big holes" in the pentlandite structure. It will also be observed that the pentlandite S atoms in Fig. 5 are complementary to those in Fig. 4. The two together being equal to those of pyrrhotite. The sequence of the (111) planes in pentlandite is: metal plane, S plane (Fig. 4), S plane (Fig. 5), metal plane. The distance between the two S planes is twice that between S and metal planes. The good (111) cleavage of pentlandite probably would pass between the S planes. The arrangement of the S atoms seems to eliminate a S contact plane as a possibility. The arrangements of the metal atoms in the (0001) and (111) planes, respectively, are in excellent agreement, however. They may be superimposed as well as the S planes in Fig. 4, but with the "holes" now filled with atoms. Still a contact plane of metal atoms is improbable, for the forces acting on some of the atoms would be much greater on one side of the contact plane than on the other, as can be seen from a study of structure models. Since no other planes in the two minerals agree as well as those discussed, oriented intergrowths are improbable if not impossible.

²⁷ The equilibrium diagram of pyrrhotite and pentlandite and their relations in natural occurrences, *Econ. Geol.*, vol. 22, 1927, p. 296.

²⁸ Alsén, Nils, Röntgenographische Untersuchung der Kristallstrukturen von Magnetkies, Breithauptit, Pentlandit, Millerit und verwandten Verbindungen, *Geologiska Fören. i. Stockholm Förh.*, vol. 47, 1925, pp. 26-62.

CONCLUSIONS

Oriented intergrowths as seen especially under the metallographic microscope are discussed. It is found that intergrowth takes place only on those crystallographic planes in which the atomic arrangement and spacing are almost alike. Differences do not exceed a few percent. At least one of the chief chemical constituents (element or radical) of the two minerals is found in both. There is good reason to believe that one of the structural planes is shared by both minerals at the contact. In the examples investigated the common contact plane seems to be an oxygen or sulphur plane. Reasons are given for the probable non-existence of oriented intergrowths in mixtures of pyrrhotite and pentlandite.

NOTES AND NEWS

APPEARANCE OF TOURMALINE IN SEDIMENTS

LEVI S. BROWN, *University of Texas.*

Through central Oklahoma the strike of the Permo-Pennsylvanian contact is nearly north and south. The regional dip is gently westward, exposing the Permian strata to the west of the contact. The basal Permian is here known as the Enid group, which comprises six formations. Of these, the lowest three, in order, are the Stillwater, the Wellington, and the Garber.

These are typical red beds. They are described simply as alternating red sandstones and shales. In specific character there is little to distinguish one formation from the other.

Recently a detailed microscopic study of the Stillwater, Wellington, and Garber formations was undertaken, looking to the establishment of some means of discrimination. The results, reported elsewhere, cannot be said to have yielded any information of specific value in this regard.

However, the "heavy" mineral fractions exhibited numerous species, including tourmaline as a fairly important constituent. Though not abundant, the mineral was present, nevertheless, in considerable variety, and its varied appearance frequently interrupted prompt recognition and counting.

The brief description of tourmaline in sediments as here observed is intended only to assist in its prompt recognition in the examination of sediments in which it may occur. The variety of form and color observed in these sediments seemed to offer a very favorable opportunity for the more complete description of its sedimentary facies. Characters described are those only of ready observation or most facile determination.

COLOR. The colors of tourmaline grains observed in these sediments include blue, light purple, deep golden brown, jet black, and colorless. This selection of colors is somewhat more limited than may be illustrated by macroscopic specimens, due, in part, to the fact that the pink variety, rubellite, is colorless in thin slices or microscopic grains. Sedimentary grains also rarely display the odd or zonary distribution of colors so frequently found in macroscopic specimens.

The jet black tourmaline is practically opaque, except in very thin flakes, and these transmit light but feebly. This variety is the one of most difficult recognition. Sedimentary grains of sizes usually dealt with are opaque, but may be demonstrated to be translucent by fracturing to very thin flakes. Luster usually serves to distinguish black tourmaline from other dark, black, or opaque mineral grains. Rotation of the microscope stage will afford some position in which the luster may be seen to advantage. It is very brilliant, giving the appearance of black obsidian. It may be distinguished from that of a truly opaque mineral by its apparent softness, or depth, as contrasted with the flat reflection seen from truly opaque surfaces.

ABSORPTION AND PLEOCHROISM. Absorption of the "O" ray is very strong in the light purple and brown varieties, weak for the blue, unobservable in the colorless, and difficultly observable in the black. Pleochroic formulae are as follows:

VARIETY	"O" RAY	"E" RAY
Light purple	Dark purplish black	Light lilac purple
Blue	Sky blue	Very pale yellow
Brown	Deep golden brown	Light orange
Black	Jet black	Greenish black

EXTERIOR FORM. There are three principal types of sedimentary tourmaline grains, as to external form; first, the somewhat elongated prismatic type, usually with fairly rounded terminations, and the two equidimensional types, one being wellrounded, and the other showing a rough and hackly fractured surface, fracture sub-conchoidal. Prismatic cleavage (Dana, 1120) is infrequently exhibited by the prismatic type, but much more commonly is this type associated with dark rod-like inclusions arranged parallel to the elongation.

ORIENTATION. The equidimensional grains are often "basal" grains, interesting in the absence of basal cleavage. Milner states the mineral to possess a basal parting. Dana records neither parting nor cleavage in the basal direction, but observes a difficult rhombohedral cleavage, (10 $\bar{1}$ 1). In this form the angle between (10 $\bar{1}$ 1) and (0001) is 27° 20.' This is a rather flat rhombohedron, and evidently a fragment originally cleaved thus might easily lie nearly in a basal orientation.

Supplementary to the above observations of cleavage and orientation, small hand specimens of several tourmalines were gently fractured. The material obtained was screened, and that passing the 100-mesh and caught on the 200-mesh critically examined. The fracturing produced evidently did not conform to any cleavage or parting, prismatic, basal, or rhombohedral. The fractured surfaces were irregular, both in form and orientation, but it is worthy of note that an important percentage of the grains were basal flakes, showing good interference figures. Accurate estimation of this ratio is difficult for the entire specimen, but of the size examined from 15% to 25% of the separate grains were thus oriented.

The characters above noted are those that may be quickly noted in routine examination of numerous sedimentary specimens. As to the use of the mineral in the correlation attempted in this case, little is to be said. No distinctive features or amounts appeared in any horizon. The variety of form and color is believed to indicate a blending of different sediments in the last of several cycles of erosion and re-deposition. This being the case it would be interesting to determine the original sources of the various species, by tracing the stratigraphic units laterally, and this is to be attempted in a later investigation.

An interesting booklet on the Economic Outlook for the Basic Industries of Pennsylvania has recently been prepared by the School of Mines and Metallurgy of the Pennsylvania State College. The purpose and contents of this pamphlet are briefly summarized in the following paragraph taken from the Foreword. "This booklet has been prepared to promote the mining and the mineral industries of Pennsylvania with a view of cultivating more favorable public opinion. The first part covers the great economic importance of the mining and the mineral industries of the State, and the urgent need for more technical application; the second part tells of the advisory board program which serves as a connecting link

between state industry and state education; and the third part outlines the service that the Pennsylvania State College is rendering to the mining and the mineral industries add to the people of Pennsylvania." Copies of this bulletin can be secured by writing the Dean, School of Mines and Metallurgy, State College, Pa.

Dr. Max von Laue, professor of theoretical physics in the University of Berlin, and Dr. Arnold Sommerfeld, professor of theoretical physics in the University of Munich, have been elected honorary members of the Leningrad Academy of Sciences.

On March 21 the U. S. Geological Survey celebrated its fiftieth anniversary. Clarence King was appointed the first director on March 21, 1879. The appropriations for the work of the Survey have increased from \$100,000 for the fiscal year 1880 to over \$2,000,000 for the fiscal year 1930.

The Council of the Geological Society of America has decided to hold the next annual meeting in Washington, D. C., Thursday to Saturday, December 26-28, 1929. The Mayflower Hotel will be the headquarters of the Society, and the regular scientific sessions, as well as the annual dinner, will be held in the same place. The Mineralogical Society of America will hold its meetings at the same time.

REVIEWS

ÜBER DIE RAUMGRUPPE DES STAUROLITHS UND SEINE GESETZMÄSSIGE VERWACHSUNG MIT CYANIT. GABRIEL MARTIN CARDOSO. *Berichte über die Verhand. d. Säch. Akad. d. Wissenschaften z. Leipzig, math.-phys. Klasse.* Vol. 80, pp. 165-199, 1928. Price 2.80 R.M. Verlag von S. Hirzel.

The dimensions of the unit cell of staurolite are given as $a_0 = 7.81\text{\AA}$, $b_0 = 16.59\text{\AA}$, $c_0 = 5.64\text{\AA}$. They correspond to an axial ratio of 0.4726:1:0.3400. The value for the c axis is, therefore, half of that usually given. Two molecules of Niggli's formula $(\text{SiO}_6)_4\text{Al}_9\text{Fe}_2\text{H}$ can be accommodated in the unit cell. The formula $\text{Si}_2\text{Al}_6\text{FeHO}_{13}$ gives no satisfactory values. C.*Gottfried's space group V_h^{11} is probably wrong. V_h^{17} seems to be correct. The well known crystallographic intergrowth of staurolite and cyanite is explained by the pseudo-orthorhombic character of cyanite. Intergrowth takes place along the plane (010) of staurolite and (100) of cyanite. This causes the b axis of cyanite to be nearly parallel (difference $5\frac{1}{2}'$) to the a axis of staurolite. A normal to the plane of the b and c axes of cyanite almost coincides with the crystallographic direction [411]. X-ray study shows that this direction is a relatively short primitive translation or, in other words, a line of relatively close atomic spacing. By using this direction as the a axis in the pseudo-orthorhombic unit cell of cyanite we have $a_0 = [411] = 26.87\text{\AA}$, $b_0 = [010] = 7.88\text{\AA}$, $c_0 = [001] = 5.65\text{\AA}$.

Comparison with staurolite shows that the translations along the c axes are almost identical and that the translation of staurolite along the a axis is almost the same as along the b axis in cyanite. The two minerals, then, have almost identical primitive translation in the plane which is common to both when intergrown.

JOHN W. GRUNER

BEZIEHUNGEN ZWISCHEN LICHTBRECHUNG, DICHTHE UND CHEMISCHER ZUSAMMENSETZUNG IN DER GRANATGRUPPE. H. V. PHILIPSBORN. *Abhandl. d. math.-phys. Klasse d. Säch. Akad. d. Wissensch.*, Nr. III, vol. 40, 1928. 42 pages, 15 figs. Price 2.50 R.M. Verlag von S. Hirzel.

The number of components that need to be considered in the relationships of chemical composition to refraction of light and density in the garnet group is discussed. It is shown that only three components are sufficient, if no fourth component is present in amounts exceeding 2 per cent. Tetrahedral diagrams are used for plotting the four components, pyrope, grossularite, almandite and andradite. The diagrams show planes of equal refraction, planes of equal specific gravity, and planes of equal dispersion of light ($n_{Li}-n_{Ti}$). A number of examples are given to illustrate their use in finding the percentages of components for a given garnet. The analyses are to be published in another paper. Sixteen new measurements for dispersion in garnets are added. Many numerical tables for the construction of large tetrahedral diagrams to insure greater accuracy are contained in the paper. The use of X-ray powder diagrams for the interpretation of the composition of garnets is discouraged because it does not offer sufficient accuracy. Finally the graphical solution for five component isomorphous mixtures (addition of spessartite or uvarovite) is discussed.

JOHN W. GRUNER

THE DETERMINATION OF MINERALS UNDER THE MICROSCOPE. JOHN W. EVANS. 110 pages, 51 figures including 4 plates, and frontispiece. Thomas Murby & Co., London, 1927.

This book as stated in the preface represents "a revision and amplification of communications on the same subject published in the Proceedings of the Geologists' Association, 1909, Vol. XXI, pp. 79-94, and in the *Journal of the Quekett Club*, 1915, Vol. XII, pp. 597-630." It is a non-mathematical, elementary text dealing with the principles of optical mineralogy.

The ten chapters have the following headings: The Petrological Microscope; The Nature and Properties of Light; Examination of Minerals in Polarized Light; Phenomena between Crossed Nicols; The Object Image; The Directions Image; Dispersion in the Directions Image; Other Determinations; Summary of Procedure; and Minute Crystals, Grains, and Fragments of Minerals.

The text will be found helpful to students of crystal optics although the beginner may find, in places, the style somewhat involved.

W. F. H.

THE GENESIS OF SOME TYPES OF FELDSPAR FROM GRANITE PEGMATITES. OLAF ANDERSEN. Reprinted from *Norsk geologisk tidsskrift*. B. X, h. 1-2, 1928, pages 116-205, 9 plates, in English.

Dr. Andersen recognizes that "perthites may have been formed largely through three different processes: (1) simultaneous crystallization, (2) exsolution, and (3) replacement." The first and second theories are based upon hypothetical phase rule diagrams. He believes that notwithstanding the stimulation which these diagrams have had on feldspar investigations, their importance as expressions of actual phase relations has been exaggerated. Hence, he attempts to discuss some of the feldspar problems independent of the hypothetical phase rule diagrams.

In 1885 Lehmann suggested that perthites were formed in connection with contraction cracks. Andersen reproduces the thermal expansion curves of six feldspars as determined by Kôzu and Saiki. The thermal expansion of five of these specimens was determined in three directions: *a*-axis, *b*-axis, and the direction perpendicular to (001). The temperature range was from normal to 1000°C. The direction along the *a*-axis showed a greater expansion. The direction of maximum expansion in the alkali feldspars lies in the plane of symmetry (assuming these feldspars to be monoclinic), at an angle of 18° to 20° to (001). The direction perpendicular to the axis of maximum expansion coincides with the orientation of many perthite intergrowths.

Andersen argues that on contraction due to loss of heat, a number of parallel cracks would be produced in the direction of maximum expansion before it is attained in other directions, but the direction of maximum expansion would also be the direction of maximum stress. On further cooling it may be assumed that cracks transverse to the direction of the mean expansion will occur. By these two systems of cracks the feldspar is divided into a number of rectangular blocks. It is along these cracks that the pegmatitic solutions can enter and bring about a replacement. He recognizes that the crystallization history of pegmatites is a complicated affair.

A large portion of the paper is devoted to a description of chemical and optical studies of feldspars from granite pegmatites of Norway. He uses a number of interesting terms in connection with these. (1) String perthite, where the blebs of albite form very small narrow rods. (2) Film perthite, where the blebs assume thin plates running in a direction perpendicular to (010) to an angle of about 73° to (001). He notes other directions which these films may take. (3) Vein perthite, which is self explanatory. (4) Patch perthite. It is allied genetically with the vein perthite. The blebs are elongated in the direction of the *b*-axis as well as the *c*-axis. He also mentions interlocking perthite and antiperthite.

There are 48 very fine photomicrographs of different types of feldspars from Norway.

I would point out that the small irregularities or cusps in the thermal expansion curves of Kôzu and Saiki have been ignored by Andersen. Kôzu and Saiki indicate in their table¹ that there are optical and thermal expansion changes at certain critical temperatures, and I² have shown that these critical points can be fitted in with the suggestions of Winchell.³

Andersen's recent contribution to the feldspar problem is a very helpful paper and should be consulted by all those interested in these minerals. It should be emphasized, however, that the theory of replacement to explain perthites should be chiefly confined to perthites of pegmatitic origin. Andersen's paper deals with feldspars from pegmatites, yet, I fear that many mineralogists and petrographers may assume that all perthites are due to replacement and ignore the other theories of simultaneous crystallization and exsolution. I believe there are many feldspars which have to be explained by using all of the above mentioned theories.

HAROLD L. ALLING

¹ S. Kôzu and S. Saiki, *Sci. Repts., Tohoku Imp. Univ.*, Ser. III, Vol. 2, No. 3, 1925, page 235.

² *Jour. Geol.*, Vol. 34, 1926, page 602.

³ *Jour. Geol.*, Vol. 33, 1925, pages 714-727.

PROCEEDINGS OF SOCIETIES

PHILADELPHIA MINERALOGICAL SOCIETY

Academy of Natural Sciences, April 4, 1929.

A stated meeting of the Philadelphia Mineralogical Society was held on the above date with the president, Mr. Trudell, in the chair. Fifty-five persons were present, including thirty-nine members.

Upon favorable recommendation of the council the following were elected junior members: Messrs. Ruben Loebel, Theodore Grau, and F. Schwan. Mr. Oldach presented the names of Robert Bradley, and Jack Simless; and Mr. Cienkowski proposed the name of Mr. Edward Wojtowicz. Mr. Biernbaum outlined the details of the proposed competitive exhibit of minerals by High School boys. Supplementary remarks were contributed by Messrs. Toothaker and Cienkowski.

The evening was then devoted to an examination of box mounts of minerals under the microscope. The members were seated about five rotating tables, each accommodating from eight to twelve persons. Each table was provided with a binocular microscope, and the exhibits, changed by one of the members, were rotated successively to each person. The mounts shown were those from the collection of Dr. L. C. Wills, who made some remarks on this phase of mineralogy.

SAMUEL G. GORDON, *Secretary*

THE MINERALOGICAL SOCIETY (ENGLAND)

Mineralogical Society, March 19, 1929. Dr. G. T. Prior, President, in the chair.

DR. A. W. GROVES AND MR. A. E. MOURANT: *Inclusions in the apatites of some igneous rocks.* Apatite crystals with dark cores of inclusions have been observed among the heavy minerals of some English sedimentary rocks, but there are few records of such apatites in igneous rocks. The authors record several such occurrences in granites and in volcanic rocks from Normandy, Jersey, and Brittany. Five different types are distinguished in the granite of northern Brittany alone. In one type with a definitely pleochroic core the inclusions appear to consist of biotite or chlorite, but in other types it has not been possible to determine their nature.

MR. L. A. NARAYANA IYER: *Calc-gneisses and cordierite-sillimanite-gneisses of Coimbatore, Madras Pres., and of similar occurrences in India.* The paper dealt with a suite of crystalline gneisses in the ancient Archaean complex of India of Dharwar age (Huronian), consisting of the above two facies, which are in close association. Similar suites of rock occur in different parts of India, forming a definite stratigraphic horizon. The author considers their formation as due to thermal or "infra-plutonic" metamorphism followed or accompanied by regional or dynamo-thermal metamorphism of pelitic schists and calcarous sediments.

MR. F. A. BANNISTER: *A relation between the density and refractive index of silicate glasses with application to the determination of imitation gemstones.* The study of simple glass families leads to a relation between the refractive index and density which can be applied in a modified form to the determination of imitation gemstones. $n \cdot N/d \cdot D$, where N and D are the refractive index and density of silica glass, is plotted against n by a simple graphical method whereupon the

various imitations separate into groups; the members comprising any one group are chemically similar. Doubtful cases can be solved by measuring in addition the relative dispersion.

MR. H. E. BUCKLEY: *The crystallization of potash-alum*. The author described the results of experiments on the differences of crystal habit obtained under varying conditions of cooling, and evaporation, and in the presence of various substances in solution.

W. CAMPBELL SMITH, *General Secretary*

NEW MINERAL NAMES

Renardite

ALFRED SCHOEP: La renardite, nouveau Minéral uranifère (Renardite, a new uranium mineral). *Bull. Soc. Min. Fran.*, **51**, 1-6, 1928.

NAME: In honor of A. F. Renard, formerly professor of mineralogy at the University of Gand.

CHEMICAL PROPERTIES: A hydrous phosphate of uranium and lead, $\text{PbO} \cdot 4\text{UO}_3 \cdot \text{P}_2\text{O}_5 \cdot 9\text{H}_2\text{O}$. Analysis: Insol. 2.11, PbO 12.26, P_2O_5 8.15, CoO 3.68, MoO 0.74, UO_3 64.82, H_2O 8.74. Sum 100.50. In a closed tube it yields water and turns brown. Fuses on charcoal to a black scoriaceous mass. Easily soluble in hot HNO_3 , in HCl with separation of lead on cooling.

CRYSTALLOGRAPHIC PROPERTIES: Orthorhombic. $a:c=1:1.209$. Flat, rectangular prisms. Forms (100), (010), (101). Cleavage parallel to (100), perfect.

PHYSICAL AND OPTICAL PROPERTIES: Color yellow, luster greasy. Biaxial negative, plane of optic axes is parallel to (001). $X=a$, $Y=c$, $Z=b$, $\alpha=1.715$, $\beta=1.736$, $\gamma=1.739$. Dispersion $\rho>\nu$. Pleochroism $X=\text{colorless}$, $Y=\text{yellow}$, $Z=\text{yellow}$.

OCCURRENCE: Found as minute crystals with quartz, torbernite and clay from the Kasolo Mine, Katanga, Belgian Congo. Resembles dewindtite and dumotite.

W. F. FOSHAG

Chile-Loweite

W. WETZEL: Die Salzbildungen der Chilenischen Wüste (The formation of Salts in the Chilean Desert). *Chemie der Erde*, **3**, 388-389, 1928.

CHEMICAL PROPERTIES: A hydrous sodium, potassium, magnesium sulphate, $\text{K}_2\text{Na}_4\text{Mg}_2(\text{SO}_4)_6 \cdot 5\text{H}_2\text{O}$. Analysis (on impure material): K_2O 10.83, Na_2O 20.51, MgO 7.15, SO_3 43.43, N_2O_5 8.73, $\text{H}_2\text{O}-0.23$, $\text{H}_2\text{O}+9.05$.

CRYSTALLOGRAPHIC PROPERTIES: Trigonal. Habit: thin tabular to the base. $a:c=1:1.19$ ca. Forms: base and rhombohedron.

PHYSICAL AND OPTICAL PROPERTIES: Optically negative. $\epsilon=1.434$, $\omega=1.470$. Sp. Gr. 2.153 ca.

OCCURRENCE: Found in the "calichera" between the "Chile" "Alemania" works, at Taltal, Chile, as minute crystals.

W.F.F.